Acceptance of the Beam Shower Counters at the CDF Experiment

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Abstract

This document presents the efficiencies of the Beam Shower Counter at the Collider Detector at Fermilab (CDF) experiment. Simulations of proton-antiproton interactions were made in order to calculate the efficiencies. The efficiencies are important because of their relation to the luminosity and cross section. Therefore, the efficiencies will be needed for future experiments at Fermilab.

1. Introduction

The research that will be discussed in this paper is part of the branch of experimental physics called High Energy Physics or Particle Physics, dealing with fundamental particles and their interactions. The specific project involves simulations of proton-antiproton ($p\bar{p}$) collisions with little bias in the particular type of interaction, so-called minimum bias (minbias) event. Once the simulations are made, we calculate the efficiencies of the detectors and the errors of such measures. Those efficiencies will be needed to conduct experiments such as Run-II at Fermilab, because they are related to important quantities like the number of collisions, the luminosity, and therefore the cross section. The next sections will discuss what we simulate, the meaning of the important quantities for this task, how we perform the simulations, and finally the results we obtain.

1.1 The Tevatron

The simulations create an environment similar to that of the CDF and to that of the Tevatron. In Fermilab, and therefore in our simulations, the process of making proton-antiproton collisions can be summarized as follows. Antiprotons are produced by slamming high-energy protons (the nucleus of H atoms) into a target; one of the products of those collisions is the antiproton. Once sufficient numbers of antiprotons have accumulated, they are injected into the Main Ring. There both, protons and antiprotons, can be accelerated up to energies of 120 billion electron volts (GeV); then they can be injected in the Tevatron, which is another ring-shaped accelerator that can accelerate particles to an energy of 1TeV (1000GeV). Therefore, the experiment consists of two different beams of particles (p and pbar) that collide at certain points. The CDF experiment, which is a whole set of detectors, is located at one of these collision points while D0 occupies another [1,2].

1.2 The interactions

As we mentioned before, we simulated collisions of particles. The simulations were designed with the intent of emulating minimum bias $p\bar{p}$ inelastic collisions. A minimum bias is the sum of all possible proton-antiproton interactions, with their respective products. An illustration of such a collision using Feynman diagrams can be seen in Figure 1. There we see that the X represents the proton remnant.

To explain the results of this project, we must introduce the terms for different types of interaction. Inelastic collisions are those in which particles collide and they break up producing other particles. A hard scattering interaction occurs when for example, a proton collides with another particle and then the proton breaks up into its constituents (quarks and gluons). Those constituents then collide with each other. In a single diffraction scattering, one of the two particles that interact is excited into resonance and the other is left intact. Then the one that was excited decays into other particles. In double diffraction scattering, both of the particles that interact are excited and both decay [2]. Feynman diagrams of these last two types of interactions can be seen in Figures 2 and 3 respectively.

1.3 The detectors

The detectors are devices designed to detect the products (particles) that originate from collisions. There exist many kinds of detectors, but the one that we studied in our simulations was the Beam Shower Counter 1 (BSC-1). It is called the BSC-1 because there are other three similar detectors located at other positions relative to the beampipe (the tube in which $p\bar{p}$ collisions occurs). This detector consists of two scintillation counters, each counter connected to its own photomultiplier tube. The scintillator material is SCSN-81 (a kind of plastic), and it is preceded by a lead plate. The BSC-1 detects particles coming in any direction from the interaction point, but at very small angles relative to the beampipe [4]. The scintillator works in the following manner: when a particle interacts with the scintillator material, it excites the molecules of the fluorescent particles, which emits photons that are detected by the photomultiplier. The overall shape of the BSC-1 can be seen in Figure 4.

Is also relevant to mention another detector that, although it was not part of our simulations, will play an important part in future experiments at Fermilab. It is the Cherenkov Luminosity Counter (CLC), which possesses all the advantages of the BSC-1 with the added ability to select and count particles coming directly from the interaction point. Therefore, it can achieve smaller uncertainties in the luminosity measurements than the BSC-1. The detector consists of a set of conical shaped tubes made of mylar, coated with aluminum, and filled with a gas (isobutane, in this case) [5]. It works as follows: a particle enters a tube from the interaction point. If its velocity in that medium is greater than the speed of light in that medium, it begins to emit photons (Cherenkov radiation). The phenomenon is similar to the sonic boom when an object goes faster than the speed of sound. Those photons are detected at the other side of the tube by a photomultiplier.

2. Cross Section, Luminosity, and Efficiency

This section explains some details of the experiments on which our research is based, the key quantities that we were trying to obtain from the simulations, and why they are important.

2.1 Cross Section and Luminosity

The *cross section* (σ) is the effective area a target presents to a high-energy particle (measured in barns = 10^{-24}cm^2) [1]. It is a key quantity in experimental particle physics for many reasons. First, it can also be calculated theoretically using Feynman rules, which are applied to Feynman diagrams. A Feynman diagram is a graphical method of representing an interaction, but if we apply Feynman rules to the diagram, the diagram is transformed into a precise mathematical notation (giving the elements of a matrix which describes the interaction) [2]. An example of a Feynman diagram is shown in Figure 1.

Therefore, if we calculate the cross section from experimental data we have a way to determine how well theory describes natural phenomena. Secondly, the cross section is also important because it is used as a unit to compare the relative probabilities of different types of interactions during a collision [1].

The *number of collisions* (N_c) is another important quantity because it is used in the calculation of the luminosity. The importance of both quantities lies in the fact that they are used to calculate the cross section using experimental data. The *luminosity* ($\mathcal{L}$) is a quantity that describes how intense the beams of particles are before they interact with each other (i.e., it describes the energy flux); it is measured in $cm^{-2}(sec^{-1})$ [1]. The basic formula for the instantaneous luminosity is

$$\mathcal{L} = N_{ppbar} \big/ (\Delta t)\sigma_{inel} \tag{1}$$

where N_{ppbar} is the number of inelastic $p\bar{p}$ interactions in time Δt, and σ_{inel} is the $p\bar{p}$ inelastic cross section.

2.2 Efficiency.

The BSC-1 cannot detect 100% of the number of collisions or $p\bar{p}$ interactions, hence the interest in calculating the efficiencies of the detectors. Efficiency is defined in this case as

$$\varepsilon \equiv N_{\det} \big/ N_{ppbar} \tag{2}$$

where N_{det} is the number of particles that hit the detector.

When an experiment is conducted, the detectors can measure the number of collisions per unit time or the *rate* ($N_{ppbar}/\Delta t$), which is related to the luminosity and the cross section by the following equation:

$$rate = \frac{dN_{p\bar{p}}}{dt} = \mathcal{L}(\sigma) \qquad [s^{-1}] = [cm^{-2}s^{-1}]*[cm^{2}]. \tag{3}$$

If we integrate that equation with respect to time and already know a cross section for the minbias reaction, the above equation can be solved (recall that the cross section is time independent) for what is now the integrated luminosity (L). That gives us the following equation:

$$L \equiv \int \mathcal{L}\, dt = N_{p\bar{p}} \big/ \sigma_{inel} \,. \tag{4}$$

However, since the BSC cannot detect all the collisions that took place, we must insert the efficiencies of the detectors into equation (4) to have the correct value for L. So we have

$$L = N_{p\bar{p}} \big/ \sigma_{inel} = N_{\det} \big/ \varepsilon \sigma_{inel} \; . \tag{5}$$

Using the measured luminosity and Eq. (3), we can obtain cross sections for other reactions that may also happen when a proton-antiproton interaction occurs.

3. Details of the simulations

We have already explained the importance of the efficiencies, but now we must discuss how we estimate those numbers. The efficiencies can be calculated from experimental data or from simulations. In this case, we made simulations, because from them we can obtain reliable data predictions for a large variety of different physical conditions. Hence, the results of this project came from many simulations that were made under a variety of conditions. In all of the simulations, we set the number of interactions or events (N_{ppbar}) to 10,000. This number was chosen in part arbitrarily. However, were also interested in simulating a number of events that yield a low error in the estimation of the efficiencies, while limiting the computer time required. The process of making a computer simulation of a proton-antiproton interaction is a complex one, so it will be helpful to divide that process in two parts: the simulation of the $p\bar{p}$ interaction and the evolution of the produced particles as they traverse the detectors. The following sections are devoted to describe the simulation process.

3.1 The Event Generators

The event generators are in simple terms the software that is in charge of generating the proton-antiproton inelastic collision or event. In this project we used two different event generators: Pythia and MBR (Minimum Bias event generator). They use Monte Carlo techniques, but each of them uses different physics models for some effects that cannot be calculated pertubatively, effects such as hadronization (transformation of quarks and gluons into particles).

3.15 The Monte Carlo technique.

Monte Carlo techniques are computational methods that were invented to solve a wide set of complex problems that otherwise would be very difficult or even impossible to solve. We can say briefly that this technique involves four components: statistics, probability, random numbers, and computer simulations.

In rough terms, Monte Carlo Techniques work in the following way. A given process in which we will apply the technique is simulated using random numbers generated in the interval [0,1]. The Monte Carlo technique transforms that random number into a number sampled from another probability distribution, the one that best describes our problem (in this case the $p\bar{p}$ interaction). There are three basic methods for performing such a transformation, but we will not get into the details of each method [3].

3.2 The GEANT simulation tool.

To this point, we have focused on just a part of the simulation, the initial proton-antiproton interaction. However, once the $p\bar{p}$ interaction occurs many other particles come out as a product of the collision. Keeping in mind that we are simulating a beam of protons colliding with another beam of antiprotons, it is easy to see that the situation becomes quite complex. Therefore, this section is devoted to how the interaction of the products of the collision with the detectors (the BSC-1) is simulated. The software used to make the simulations was GEANT 3.21, developed at CERN (European Organization for Nuclear Research). GEANT is used primarily to make drawings of experimental setups and particles trajectories, and to simulate the transport of particles through a given detectors setup. In this project, we focus on the second of these applications. Also it is important to mention that the program uses Monte Carlo techniques for both tasks.

The GEANT program consists of many subroutines (i.e., a subprogram that may return a single, many, or no values to the main program [6]) written in FORTRAN 77. The user calls these subroutines, and inserts the appropriate information according to what he/she wants to simulate. To better explain how GEANT runs its part in the simulation, we should mention the three phases of its operation: initialization, event processing, and termination. Different subroutines are in charge of running each of the phases [7].

Finally, it is important to note that to obtain a graphical representation of the experimental setup and of the particles trajectories, we use the interactive version of GEANT (GEANT++). The details of how GEANT++ works will not be presented in this document. An illustration of the experimental setup that we simulate and of the particles colliding with the detector can be seen in Figures 5 and 6 respectively.

4. Results

The goal of this project was to make diverse simulations of how the BSC-1 detectors work to estimate their efficiency. We simulate an array of four detectors around the interaction point (IP) in the beampipe (see Figure 5). In Table 1, we can see the efficiencies of the detectors for each simulated run. Each run as it is explained in the table has different physical conditions. The BSC-1 can be divided in two quadrants, one for each scintillator counter. The average efficiencies were calculated for different combinations of the quadrants. The combinations that will be used in future experiments (Run-II) at Fermilab are either two or three quadrants in coincidence with another two or three quadrants. This is the preferred combination because it provides a way to discriminate between particles coming from the IP and particles coming from elsewhere. Quadrants in coincidence means that the computer will count a collision if particles coming from the IP hit both of the quadrants, in detectors that are at diagonal opposing sites relative to each other.

The uncertainty of the efficiencies is also given in both tables, and it was calculated using the following equation:

$$\sigma = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}} \tag{6}$$

where σ is the uncertainty (a standard deviation for the binomial distribution applied to this case), ε is the calculated average efficiency, and N which is equal to10000 is the total number of collisions in for the simulation.

Some important conclusions can be drawn from the data in Table 1. For example, consider the sixth and seventh runs in the table. The difference between these runs is merely the size of the flanges in the beampipe. It is clear from our results that the flange size does not greatly affect the efiiciencies. Although we double the size of such bumps, the difference between the efficiencies of the two cases is 1% or less (0.17% on average). The fact that the size of the flanges does not greatly affect the efficiencies is good because we have flanges in the real beampipe and they are difficult to measure. On the other hand, if a comparison is made between the 11th and 12th runs it is obvious that the difference is significant, of about 24.5% in average. Therefore, we see that the efficiency has a strong dependence on the kinds of interaction that may occur between the proton and the antiproton.

We stated above that the efficiencies of greatest interest are those for two or three quadrants in coincidence. For the case of two quadrants in coincidence, Table 1 shows efficiencies around 30% with the exceptions of three cases in which the efficiencies are in the range of 16 to 20 % and one other case in which the efficiencies drop to less than 1%.

For the situation of three quadrants in coincidence, it is seen that efficiencies are around 40% with the exceptions of two cases of approximately 21%, one case of 29%, and again one case of less than 1%.

Table 2 presents the efficiencies for the same set of conditions as the last run of Table 1, but this time we added one of two different energy thresholds for the collisions. The last of the Pythia runs of Table 1 effectively corresponds to a threshold of 0MeV. One can see from Table 2 that introducing a 0.5MeV threshold reduces the efficiency by about 3%, and increasing the threshold to 1.0MeV produces a further 3% reduction.

In summary, we have accomplished the goal of calculating the efficiency for the BSC-1 detector. This information is important for the calculation of how frequently a particular type of interaction occurs. Future work on this project is needed to include other detectors such as the CLC that were not part of this work, and to improve the simulation of the detectors’ response to the incoming particles.

References

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Table #2

Efficiencies found with the PYTHIA generator, using different energy thresholds

Energy Threshold (MeV)	$<E_1>$	$<E_2>$	$<E_3>$	$<E_4>$	$<E_{22}>$	$<E_{33}>$	sigma
1.0	0.31	0.48	0.58	0.62	0.21±0.04	0.25	±0.05
0.5	0.37	0.58	0.54	0.56	0.26±0.04	0.35	±0.05

LEGEND

The characteristics of the run are the same as those of the last of the PYTHIA runs described in Table 1.

See Table 1 for the definition of all symbols.

Table 2

Efficiencies of a run with the PYTHIA generator but taking different energy thresholds.

Energy Threshold (MeV)	$<E_1>$	$<E_2>$	$<E_3>$	$<E_4>$	$<E_{2*2}>$	$<E_{3*3}>$	sigma
1.0	0.311	0.480	0.568	0.632	0.231 ± 0.004	0.325	± 0.005
0.5	0.337	0.508	0.594	0.656	0.266 ± 0.004	0.355	± 0.005

LEGEND

The characteristics of the run are the same of those of the last of the PYTHIA runs described on Table 1.
See Table 1 for the definition of all symbols.

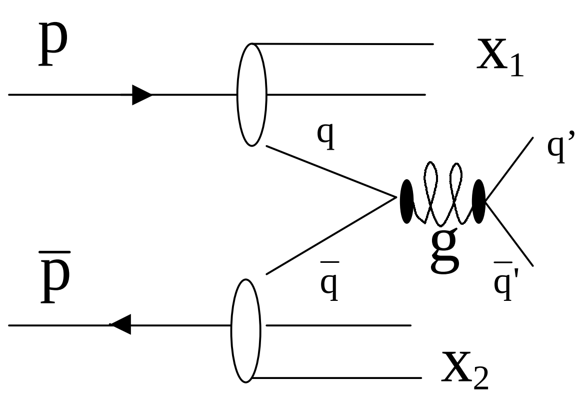

Figure 1: A proton-antiproton interaction, giving a product X. Also shown is the interaction between quarks within the proton and antiproton.

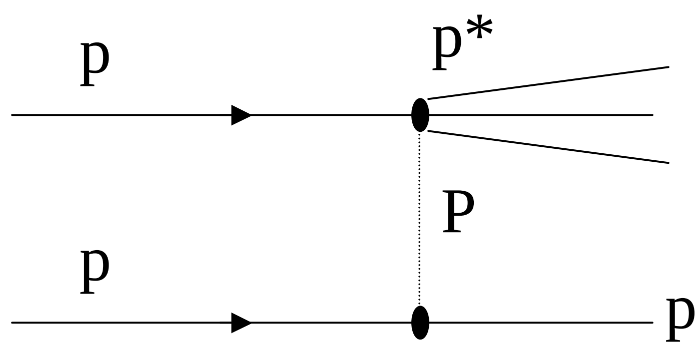

Figure 2: An example of single diffraction scattering. The p* stands for an excited proton that decays, and the capital P for a Pomeron exchange.

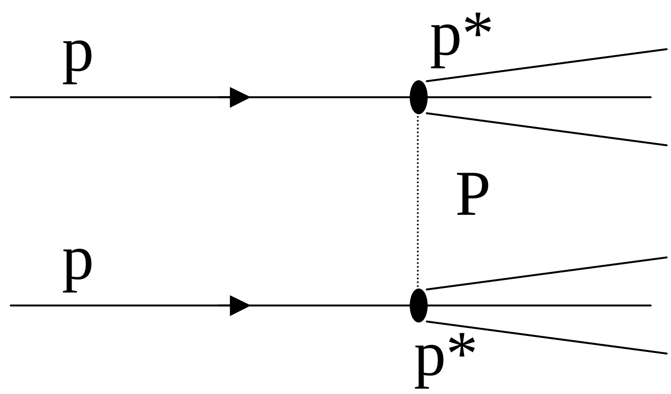

Figure 3: An example of double diffraction scattering.

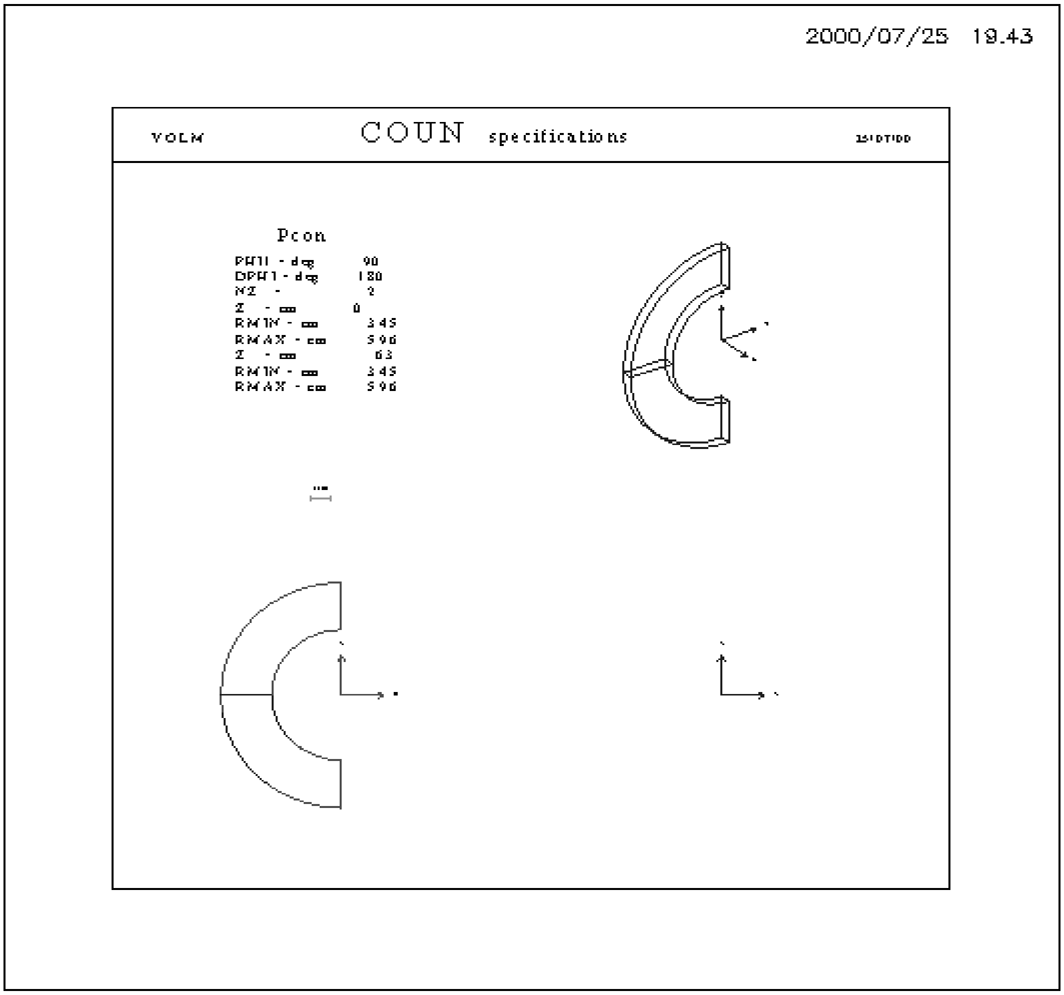

Figure 4: Diagram showing the dimensions of the BSC-1.

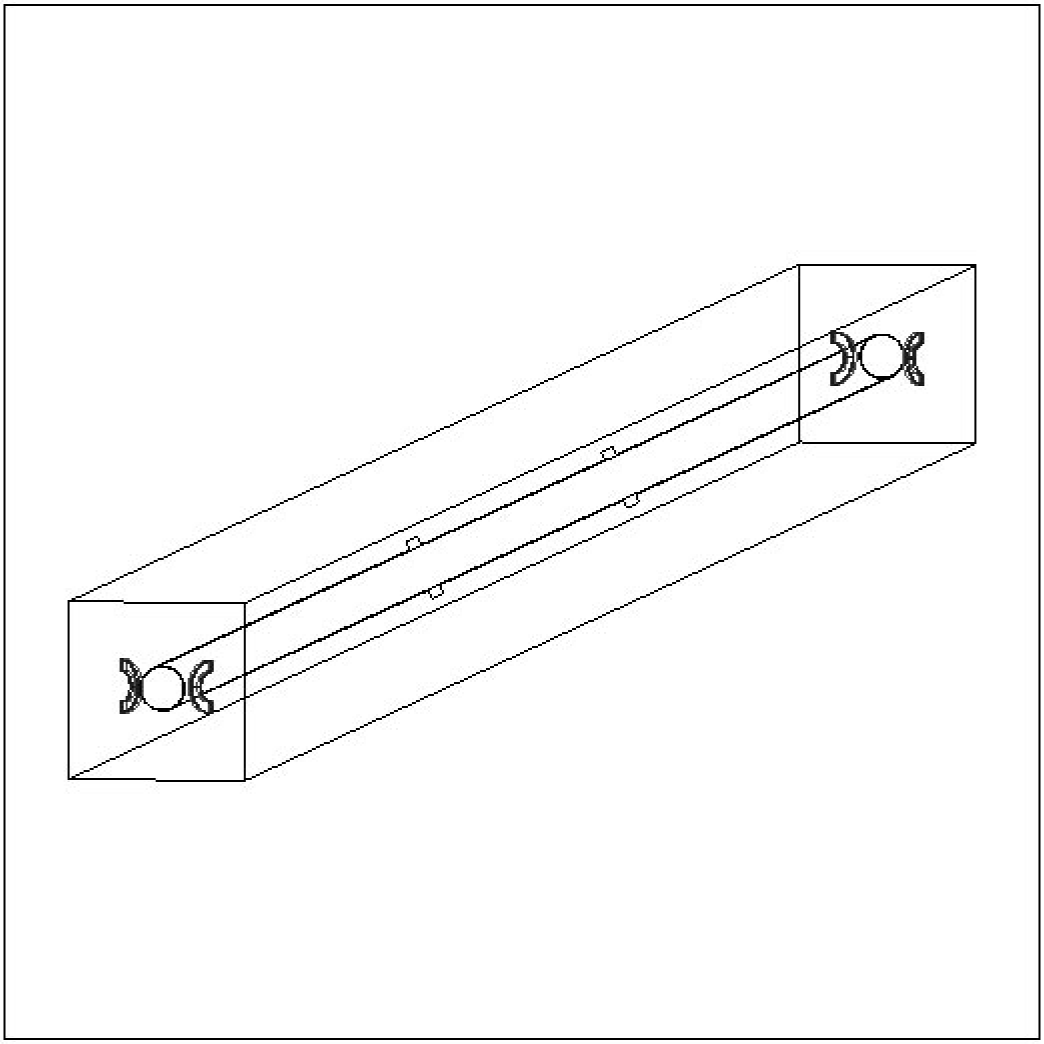

Figure 5: Image of a simulated beampipe with detectors, made using the GEANT++ package.

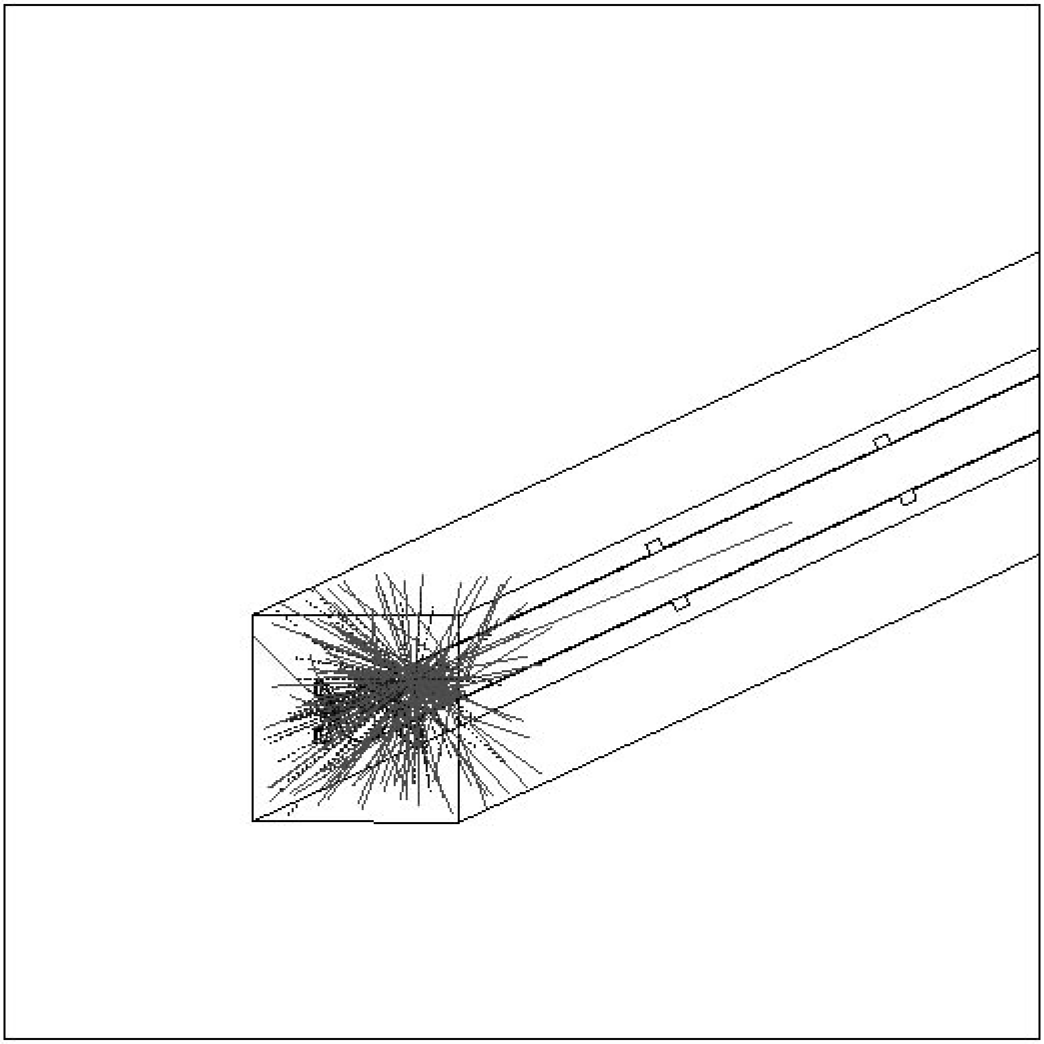

Figure 6: Close-up of the beampipe with one particle coming from interaction point. That particle produces more particles as it interacts with the beampipe.